CHAPTER ELEVEN: SUMMARY OF ENGINEERING LESSONS

11.1 Introduction

This chapter presents a summary overview of the principal technical lessons and findings from this investigation. The next three chapters that follow then carry forward a study of the underlying organizational, institutional, political, economic, human factors and decision-making issues that arise in conjunction with these "engineering" lessons and findings.

11.2 Overarching Strategic Issues

11.2.1 Targeted Levels of Safety and Reliability

Figure 11.1 shows a "risk plot" with the vertical axis representing the annual likelihood of failure, and the horizontal axis representing the expected cost of such failure either in dollars (bottom axis) or in lives lost (top axis). This figure shows the ranges of risk, or reliability, representing common practice for a number of areas of human endeavor. Highlighted with a heavy red dashed line near the bottom is current U. S. practice in the field of dam engineering.

Also shown on this plot is our investigation's view of the level of reliability associated with the New Orleans regional flood protection systems prior to hurricane Katrina. Our best estimate, based on information currently available, and given the targeted design levels and the flaws and vulnerabilities embedded in the system, is that the pre-Katrina system was likely to fail catastrophically approximately every 30 to 75 years. The cost of the failure (in hurricane Katrina) was on the order of $100 to $200 billion in losses, and approximately 1,500 lives were lost.

There is a stark contrast between the levels of reliability for which major U.S. dams are engineered, and the level of reliability of the New Orleans levee systems. This is true, to only slightly varying degree, for most levee and flood protection systems across the entire nation.

"Dams" are engineered to very high levels of reliability because their potential failure would threaten large numbers of lives, and large economic losses as well. Few dams protect (or threaten) populations as large as the combined greater New Orleans and adjoining Jefferson parish region, however, and simple logic would suggest that flood protection systems defending large populations like this should be targeted at similar levels of safety or reliability.

As indicated by the large arrow in Figure 11.1, the difference between the level of risk (or reliability) of the New Orleans regional flood protection systems and conventional U.S. dam practice is approximately three orders of magnitude; a factor of roughly 1,000 times safer and more reliable. Reliability is a function of two sub-elements: (1) the targeted level of loading(s) to be handled, and (2) the reliability with which that target is met. Achieving significantly higher levels of reliability for complex regional flood protection systems like that of the New Orleans region would require major improvements in both sub-elements.

The New Orleans regional flood protection systems were never specifically targeted at any given level of reliability with regard to formal definition of storm levels for design (e.g.: the Standard Project Hurricane was never quantified as a "100-year storm" or a "300-year storm", etc.), and this was a lapse, as it put the design of the regional flood protection system out of step with current practice. Our assessment in plotting the pre-Katrina New Orleans case in Figure 11.1 is that the system as it existed was likely to be failed by roughly the 30-year to the 75-year (average recurrence interval) storm.

The actual design intent was for more, though how much more was never formally defined.

In addition, the system did not perform as intended; multiple failures occurred at levels of storm surge and wave loading that were less than or equal to what many of the failed system elements had been intended to safely handle.

If the system is re-engineered to safely (successfully) handle a 100-year storm (storm loading likely to be exceeded typically once every 100 years), then the large red area of Figure 11.1 would move to the location shown by the light blue area in Figure 11.2. That would not bring the level of safety and reliability anywhere near to current U.S. practice for dams. Targeting a 1,000-year level of flood protection, and achieving that level, would result in the darker blue zone in Figure 11.2.

There are some significant challenges involved at the decision-making and policy levels regarding appropriate levels of safety (e.g. storm levels) for which such systems should be designed, and the degree to which resources should be committed to achieve this.

The other element of risk/reliability is the degree to which targeted design levels are successfully achieved. Levels of success were not good in hurricane Katrina; numerous failures occurred at storm surge and wave levels less than or equal to those for which the flood protection system elements were intended to be designed. These failures occurred because margins for error (e.g.: design Factors of Safety) were inappropriately small, because decisions were made to reduce costs in exchange for increased levels of risk, and because of errors and lapses in design, construction and maintenance. These types of "engineering" issues are discussed in Section 11.3 that follows.

11.2.2 Funding and Appropriations

A second set of overarching considerations are those associated with the Byzantine process by which large, complex, regional-scale flood protection systems are conceived, approved, designed, funded, constructed, maintained and operated. No useful discussion of engineering challenges can proceed without noting the tremendous additional difficulties that arise due to these types of "non-engineering" issues.

Figure 11.3 presents a very simplified schematic illustration of the principal "technical" steps involved in creating and operating a regional flood protection system (left side of the figure, in blue), and also the corollary political, organizational, institutional, engineering and construction units and entities (right side of the figure, in green) that must interact to foment this process. This is discussed in detail in Chapters 12 through 14, so we will simply note here that it is not realistic to assume that we can achieve the significant improvement of the safety and reliability of the New Orleans regional flood protection system that appears warranted simply by making adjustments to the "technical" side of this figure. Simply revising design manuals and engineering procedures, etc., cannot possibly achieve the significant improvement in system reliability that should be sought; significant improvements on the right-hand side of this figure will be needed as well.

These issues are addressed in Chapters 12 through 14, but several key issues warrant special mention at this stage. The first of these is funding and appropriations; the allocation of resources to the creation and operation of the regional flood protection system. This allocation of resources is, properly, the domain of the decision-making bodies involved; elected representatives (government) at both the federal and local levels. Unfortunately, these elected officials often lose track of the ramifications of their decisions with regard to complex technical systems created and operated over long periods of time.

It should not take 50 years to construct a critical system providing life-safety for a region with a population of nearly one million people (the greater New Orleans/Jefferson parish region.) The regional flood protection system was incomplete at the time of Katrina's arrival; it was intended to be complete by the year 2015, fully 50 years after its inception in response to the catastrophic flooding of New Orleans produced by hurricane Betsy in 1965. We need to do better.

Apart from the obvious need to more rapidly and effectively provide protection for large numbers of citizens, these types of extended construction periods (covering multiple decades) wreak havoc with the actual engineering and construction of the intended systems themselves. As noted in the IPET Draft Final Report (IPET; June 1, 2006), the New Orleans regional flood protection system was largely a system in name only. Having been constructed over four-plus decades, and in innumerable individual segments and sections, it was optimistic to expect that the various inter-connecting elements would function perfectly well together. Stretching the construction over multiple decades posed major challenges with regard to progressive loss of institutional memory and expertise, and it required excessive segmentation of systems that needed to function literally seamlessly as contiguous defenses.

Another difficult issue was the nearly constant pressure to reduce costs. Decisions that produced reductions in the costs of specific flood protection elements routinely resulted in corollary increases in levels of risk; the increased likelihood that the system would not perform well when eventually tested. As discussed in Section 11.3, this type of trade-off between short-term cost reductions and increased risk now appears very hard to justify, as it contributed significantly to many of the specific failures and breaches during hurricane Katrina, and resulted in catastrophic losses that now dwarf the short-term savings by two orders of magnitude and more.

11.3 Principal Engineering Findings and Lessons

11.3.1 Introduction and Overview

Figure 11.4 shows an overview of the New Orleans area, indicating the locations of the principal failures, breaches, and distressed sections of the New Orleans regional flood protection system studied in this investigation. Plaquemines parish (along the lower reach of the Mississippi River) is not included in this figure; instead it is indicated by the large arrow at the bottom. The individual features, and groups of features, in Figure 11.4 are numbered for purposes of discussion. Table 11.1 presents a summary of issues at each of these locations, using the same numbering scheme as Figure 11.4.

The New Orleans regional flood protection system failed massively and catastrophically during hurricane Katrina. Depending on how one counts individual breaches (or groups breaches extending along long frontages that were massively eroded and scoured), the number of failed sections was somewhere between three dozen to 50-plus.

For an overview of performance, the system can be roughly sub-divided into four zones. At the southern end, the flood protection systems in Plaquemines Parish were massively overwhelmed by storm surges and waves significantly more severe than they had been designed to handle.

At the east flank (fronting Lake Borgne), and in the central region (along the IHNC and the GIWW/MRGO channels) the storm loadings were approximately equal to those for which the system was intended to be designed. Design loading conditions were exceeded at some locations, especially along the Lake Borgne frontages, but intended design levels were only slightly exceed and the system might have been expected to perform better. Instead, massive and catastrophic breaches occurred at multiple locations. These were principally the result of one or more of the following: (1) insufficient crest heights (which led to, and exacerbated, overtopping problems), (2) use of inappropriate materials at some locations (materials with very poor resistance to erosion), and (3) other engineering lapses and oversights.

At the north end, along the Lake Pontchartrain frontage, storm surge levels and waves presented lesser levels of loading than the system elements were intended to safely handle. System performance was good along most of the lake frontage itself, but three catastrophic breaches occurred along the drainage canals at the north end of the main (downtown) New Orleans protected basin, and these were the principal source of approximately 85% of the floodwaters that catastrophically inundated most of that basin. These three failures, together, accounted for nearly half of the overall loss of life in this event, and a similar fraction of the overall economic losses and property damages. These three major failures on the drainage canals were the result of engineering failures in design.

Multiple issues and challenges contributed to the numerous individual failures, and these have been discussed in Chapters 3 through 10. The discussion that follows will select highlights with regard to lessons that can be extracted from this event with an eye towards effecting better system performance in the future.

11.3.2 Plaquemines Parish

Plaquemines parish is a narrow, highly exposed, and sparsely populated set of corridors along the edges of the lower reaches of the Mississippi River, extending south from New Orleans to the river's outlet in the Gulf. This protected strip, with "river" levees fronting the Mississippi River and a second, parallel set of "storm" levees facing away from the river forming a protected corridor less than a mile wide, serves to protect a number of small communities as well as utilities and pipelines. This protected corridor also provides protected access for workers and supplies servicing the large offshore oil fields out in the Gulf of Mexico.

The flood protection systems of lower Plaquemines parish were massively overtopped and overwhelmed by storm surge and storm waves that significantly exceeded design levels, and multiple breaches and failures resulted (see Chapter 5.)

Plaquemines parish is sparsely populated, with a pre-Katrina population of only about 27,000 people. Given increased public awareness of risk and exposure, less than half of these are expected to return. There are few engineering lessons to be learned from the experience of Plaquemines parish; when even well-constructed levees and floodwalls are sufficiently massively overwhelmed, failures will occur. The lesson, if anything, is one of humility in the face of nature. If there is an engineering lesson here, it is:

1. *Not all areas can be protected, and it is not economically reasonable to commit out of scale resources to the protection of some areas. We must learn to choose our battles.*

Federal policy across the nation over the past two decades has been moving increasingly away from out of scale expenditures to protect, or to insure, small populations living on marginal lands at high risk with respect to flooding. Plaquemines parish will represent an interesting case in this regard.

11.3.3 The East Flank; New Orleans East and the St. Bernard/Lower Ninth Ward Protected Areas

Major cities are different. A de facto decision has already been made to reconstruct New Orleans, and to upgrade its regional flood protection systems. Accordingly, it is now incumbent upon us to do all that we can to extract important engineering lessons from the Katrina experience, and to see that these lessons are suitably applied to efforts to improve the levels of safety and reliability of the regional flood protection systems in future events.

The main breaches that were the principal source of flooding for both the St. Bernard/Lower Ninth Ward protected area and the New Orleans East protected area were the levee frontages facing "Lake" Borgne (which is actually a bay, as it is connected directly to the Gulf of Mexico.) These are sections #2 (and 2a) and #3 in Figure 11.4, and in Table 11.1.

These two sections shared a number of fatal characteristics. Both sections were constructed largely using materials dredged from the excavations for the adjacent shipping channels (the MRGO channel and the GIWW channel, respectively), and as a result both levee frontages including large sections of levees comprised in large part of materials known to perform very poorly with regard to erosion. These unacceptably erodeable materials included sands and lightweight shell-sands, and the massive and catastrophic erosion of these materials caused the rapid failure of great lengths of levees along both the MRGO and GIWW frontages. Another commonality was the lack of swamps or cypress groves on the outboard sides of these levee frontages; features that would have served to dampen (reduce the energy and intensity) of storm-driven waves attacking these frontages. Finally, these two frontages were also, unfortunately, the two frontages that were most directly exposed to severe wind-driven waves across a large body of open water.

As a result, these two frontages failed catastrophically, and were massively eroded along multiple miles of frontage, creating long breaches through which the hurricane storm surge passed easily, and with devastating consequences for the communities of these two protected areas.

Interestingly, adjacent levee sections along these same frontages, although also overtopped, performed well; suffering relatively minor erosion and continuing to provide protection as the storm surge subsided after the period of overtopping during the relatively short-lived peak of the storm surge. These better-performing sections were levees comprised of compacted, clayey soils; soils known to have far higher intrinsic resistance to erosion (see Chapters 9 and 10.)

We know a great deal about the soil types, and the placement and compaction conditions, that lead to differing types of performance with regard to erosion. Moreover, we are now increasingly able to perform specific tests of these materials, and to make reliable engineering assessments of expected behavior with regard to erosion (see Chapters 9 and 10.)

Important lessons here include the following:

2. *The use of materials excavated from the adjacent shipping channels resulted in some initial cost-savings, but these minor cost-savings were <u>multiple orders of magnitude less</u> than the subsequent damages that occurred when these levee sections failed.* ***Short-term cost savings in construction need to be balanced against the consequent increases in risk (the consequent reduction in likely reliability) for the resulting built system.***

3. *Highly erodeable embankment (and foundation) materials represent an intrinsic hazard, and their use should be avoided in flood protection systems defending significant populations.*

4. *When the use of such materials cannot be avoided, then great care should be taken to protect the sections by means of internal cut-offs, filters, and slope face protection (armoring) on the front and back faces and on the crest as well. Even then, the use of erosion-resistant soils is to be preferred if at all possible.*

5. *Levees (and composite levee/floodwall sections) can be designed to safely withstand some degree of overtopping, and for some period of time. Hurricane storm surges, unlike river floods, typically have their "peak" over only a limited number of hours. Given the economic challenges of designing flood protection systems for very high levels of*

(infrequently occurring) storm loading; the alternative of designing flood protection systems to perform safely without admitting any water into the protected areas for an fairly high levels of loading, but with sufficient resilience that they can be "overtopped safely" (overtopped for a while during a peak storm surge, but not erode and fail catastrophically) so that the system will continue to provide protection as the peak of an unusually large storm surge passes and then subsides might also be considered. Some water would enter the protected area(s), but the amount would be limited and it could be pumped out afterwards with minimal risk to life, and manageable property damages.

At some locations (e.g. adjacent to large concrete navigation gate structures) the use of the lightweight shell-sands was deliberately specified in order to minimize differential settlements and "gapping" at the contact between the concrete gate structures and the levee embankment. Prevention of this differential settlement by use of these highly erodeable materials led to massive eroded breaches at the south side of the bayou Bienvenue gate structure, and at the north side of the bayou Bienville structure along the MRGO frontage; an example of solving one problem while exacerbating another. Thus

6. *The consequences of any engineering decisions need to be considered on a <u>system</u> basis; there is a long history of engineering failures based on unintended consequences.*

Another disturbing issue was the fact that many sections of the regional flood protection system had levee crest elevations, and concrete floodwall elevations, that were below intended design grade. This was largely a result of the 40-plus years that the design and construction of the system had been underway, and the fact that benchmarks and datums for elevation control had progressively decreased in elevation as part of large-scale overall regional subsidence over that extended period of time. As a result, many sections of the regional system had crest heights and floodwall heights as much as 1 to 2 feet below intended design grade. [An excellent treatment of this issue with regard to datums and regional subsidence is presented in the IPET Draft Final Report; IPET, June 1, 2006.] This "loss" of levee crest and floodwall height exacerbated problems associated with overtopping.

In addition, the critical levees along the MRGO frontage at the northeast edge of the St. Bernard Parish/Lower Ninth Ward protected area were well below grade along much of their length. This was not an engineering lapse, nor a problem associated with subsiding datums. These levees were being constructed in stages, to allow for settlements and consolidation (to increase the strengths of the foundation soils prior to adding the next stage of levee embankment fill.) At the time of Katrina's arrival, the USACE had long been requesting funds to place the final stage of fill along this frontage. Now it is too late.

It can be argued that this represents a tragic example of the intrinsic risk associated with over-long project durations for these types of massive, regional scale projects. Also that both White House and Congressional attention lapsed, and funds that could have been provided to complete these important levees were instead deferred, as issues elsewhere drew more urgent attention. Thus

7. *If we resolve to create and operate important flood protection systems to defend large populations, then we should commit sufficient funds and diligence to consummate this*

construction within a reasonable time span. Otherwise: (1) we are leaving populations at risk, as partially completed protection is no protection at all, (2) we invite problems that will naturally arise as a result of over-segmentation of discrete project elements that must perform perfectly well together as a contiguous system, and (3) overall system coordination and integrity will inevitably suffer as a result of progressive loss of institutional memory during the extended period of design and construction.

Finally, both of these levee frontages were "backed" by lower height secondary levees that were rapidly overtopped by the massive flows passing through the long breaches in the frontage levees. Indeed, the frontage levees failed so rapidly, and so early, that they did little to blunt the storm surge. The secondary levees were never intended to have to deal with an undiminished storm surge, and they were quickly overtopped along much of their lengths (though they were comprised of better, clayey materials and suffered admirably little damage at most locations from this massive overtopping.)

The lack of height of these internal "secondary" levees represented a wasted opportunity to provide defense in depth.

8. *As the regional system is now repaired and improved, further raising of these secondary levees would provide a potentially valuable second line of defense for the populous communities behind them. If the federal government will not fund this, then local interests should consider doing this on their own.*

These secondary levees are well-situated, and are currently comprised of good, erosion-resistant materials. The USACE has recently helped to raise the secondary levee across the middle of St. Bernard parish (the Forty Arpent levee) to Elev. +10 feet (MSL). These secondary levees should be considered part of a system along with the frontage levees, and with the ridges of high ground within their protected areas as well. The frontage levees should be designed to safely resist a considerable level of storm surge. In the unlikely event that an even greater storm surge exceeds this level, then they should be designed to overtop without eroding catastrophically, and the secondary levees should be designed and sized to entrap and water overtopping the frontage levees and so protect the populous communities. That would require coordination of levee heights, and likely of oversight agencies as well.

This, in turn, represents an example of an element of engineering that was sadly missing throughout much of the regional flood protection system; the asking of the vital question: "What if?"

There was a persistent lack of ductility and resilience throughout the regional flood protection system. Over and over, system elements and sections were designed to some specified level of loading, but no thought was given as to what would happen if that level was exceeded. Over and over, we studied sections that failed catastrophically, in a brittle manner, when for little or no increase in cost the section designs could have been modified to safely accommodate some minor exceedance of the design loading conditions, and where similarly relatively minor modifications could have rendered even more severe exceedances of the specified design loads at least far less devastating in terms of consequences for the protected communities. To a large degree, this failure to ask the important "what if?" question is a function of the rules and regulations that govern the creation of these large systems. This needs to change.

9. *Instead of working to pedantically prescribed "design levels" mandated by Congress, the USACE should be allowed (and encouraged) to constantly ask the important "What if?" question. When that leads to the awareness that minor additional effort and expense would likely result in massive improvement in overall system performance and reliability, then a feed-back mechanism should be established to allow advantage to be taken of this.*

That would be an invaluable step forward, in many areas of federal operations.

11.3.4 The Central Region; the IHNC and the GIWW/MRGO Channel Frontages

The storm surge that swelled the waters of Lake Borgne was driven west along the east-west trending shared GIWW/MRGO channel to the "T" intersection with the IHNC, raising water levels within these channels and resulting in overtopping at many locations along both banks of both of these channels. Despite this overtopping, the performance of many of the levees and floodwalls along these channels was excellent. Several major failures occurred, but most of these were not caused by overtopping, but were instead the result of other issues as described below.

Along the east-west trending GIWW/MRGO channel, overtopping produced minor to moderate erosional distress at a number of locations, but no full failures (breaches) of full height earthen levee embankments occurred. The levees along both banks of this channel appeared to be comprised primarily of compacted, clayey soils, and the good performance of these materials in the face of moderate overtopping was encouraging.

Two breaches occurred along the north bank of this channel, at Sites #4a and #4b in Figure 11.4 (and Table 11.1.) The first of these (Site #4b) was a breach at an inadequate "transition" between a long reach of full height earthen levee as it joined (abutted) a mid-rise earthen levee reach with a sheetpile-supported concrete floodwall at its crest. The transition between these two adjacent project sections was a simple sheetpile wall, of lesser height than either the earthen levee to the west, or the floodwall section to the east. As a result, overtopping was most severe over the top of the short sheetpile wall transition section, and this overtopping preferentially eroded a deeply scoured trench at the rear side of the sheetpile wall. This, in turn, reduced the lateral support at the back side of the sheetpile wall section, and the laterally unbraced sheetpile wall was then pushed sideways by the storm surge water pressures on its front (outboard) side, and it failed.

This was one of many examples of inadequate detailing of "transitions" between adjacent major project elements that resulted in poor performance, and breaches at a number of locations. Thus

10. *"Transitions" where adjacent project elements join together were routinely problematic throughout much of the regional flood protection system. Successful design and construction of two adjoining project sections counts for little if the connection between*

them is not also successfully consummated. Significantly more attention needs to be paid to these "transitions".

The second breach along this frontage (Site #4a) was a failure of a concrete floodwall. This floodwall was mainly a simple sheetpile-supported I-wall, but it had two short sections of T-wall with battered piles to provide increased rotational and lateral support. The T-wall sections performed well, but major lengths of the I-wall did not. The walls were overtopped, and the water cascaded over the walls and eroded trenches at the back sides of the walls. This, in turn, laterally unbraced the walls and some sections were laterally displaced while other sections rotated, some to a nearly fully horizontal position.

Like the situation described at Site #4b above, this overtopping did not have to result in erosion and unbracing of the floodwall. Installation of splash pads, or other erosion protection, at the rear side of the walls to prevent erosion by the water passing over the tops of the walls would have represented a relatively minor additional expense (estimated at less than 5% of the overall project section cost). The USACE felt that splash pads were disallowed; they were instructed by Congressional edict to design for a specified water level, and to install splash pads would be to provide for a higher level than that which had been authorized. In hindsight, everyone regrets this dilemma. To its credit, the USACE has already undertaken (even prior to full authorization) to install splash pads behind I-walls and/or to replace I-walls with T-walls (which have their own splash pads as a result of their inverted-T shape.) Thus

(9. Repeated): Instead of working to pedantically prescribed "design levels" mandated by Congress, the USACE should be allowed (and <u>encouraged</u>) to constantly ask the important "What if?" question. When that leads to the awareness that minor additional effort and expense would likely result massive improvement in overall system performance and reliability, then a feed-back mechanism should be established to allow advantage to be taken of this.

11. Concrete floodwalls can be designed to be safely overtopped to some considerable degree, and advantage can be taken of this in design and construction of an improved overall regional flood protection system.

Further to the west, the rise in water levels within the IHNC produced overtopping at numerous locations, and it produced a number of failures as well. The overtopping was not directly related, however, to the most significant of these failures.

Two of the largest failures during hurricane Katrina were the pair of failures on the east bank of the IHNC, at the west end of the Lower Ninth Ward (Sites #6a and 6b.) These two major breaches were studied in detail, as presented in Chapter 6; Sections 6.3.1 and 6.3.2.

Although overtopping occurred along much of this IHNC frontage, and although this overtopping produced erosion at the inboard base of the concrete floodwall (and I-wall section) at the location of the south breach, both sections failed as a result of <u>underseepage</u> rather than overtopping.

The large south breach, hundreds of feet in length, failed as a result of underseepage-induced pore pressures which weakened the foundation soils beneath the inboard toe of the levee embankment, and resulted in translational stability failure of the embankment section (pushed laterally by the risen waters in the canal.) The northern breach, which was a narrower, deeper failure, was the result of underseepage-induced hydraulic uplift ("blowout") at the inboard toe and underseepage-induced toe erosion and piping.

These conclusions contradict the findings of the IPET Draft Final Report of June 1, 2006, which found the failure of the south section to be the result of overtopping, scour at the inboard toe of the floodwall, and resultant lateral unbracing of the floodwall. The northern failure was attributed to deeper-seated semi-rotational failure of the foundation, primarily through a layer of soft clays, and this failure was assumed to have occurred surprisingly early, in order to explain observations of large amounts of water collecting on the inboard side along this frontage. The IPET report also mentions that underseepage-induced failure mechanisms were not studied, as the foundation soils were too impervious.

There was a long history of underseepage-related problems along this frontage, and it is likely that the IPET study would have pursued these if they had been so informed. Instead, they hued to the history of the local New Orleans District of the USACE, and "absolved" underseepage as a potential failure mechanism at these two important sites without bothering to perform formal analyses to study the possibility.

The IPET analyses of their preferred failure modes make no technical sense, and defy the available data regarding the strengths and stiffnesses of the soils involved (see Sections 6.3.1 and 6.3.2.) Moreover, there is a long history of problems associated with underseepage along this frontage, including both citizen issues with ponded waters and contractor's difficulties with dewatering for construction. The most stunning demonstration of the high lateral permeability of the "marsh" deposits at this location, however, is a visually spectacular reverse crevasse splay (see Figure 6.45) produced beneath the temporary repair embankment section by the relatively small <u>reverse</u> flow gradients as the protected had nearly fully drained.

As shown in Figures 6.24 and 6.47, the relatively short sheetpiles at these two sections failed to achieve adequate cut-off of underseepage flow through "marsh" strata that were tantalizingly just below the bases of these sheetpile curtains. That was a repeated theme in this event, as underseepage-induced failures, as a result of inadequate sheetpile depths (where moderate extensions of the sheetpiles would likely have prevented failure) also occurred at the two major, and devastating, breaches on the London Avenue drainage canal (Sites #10 and #11a), and an additional underseepage-induced "incipient" failure began to develop on the east bank of the London Avenue canal (Site #11b) but halted as the section on the west bank failed first, drawing down the water levels.

Inadequate sheetpile depths, as a result of overly optimistic assumptions regarding the permeability of foundation soils, were thus found at five of the most important sites, including four of the most damaging breaches that occurred during hurricane Katrina. It is time for the New Orleans District to come to grips with the potential severity of the underseepage problem. This is a major issue, not only because <u>it represents a likely</u>

remaining source of potential vulnerability throughout the remainder of the system, but also because it may obviate current cost projections for further improvement of the regional system. The types of steps needed to remedy underseepage-related vulnerability are very different from the types of actions already being undertaken to reduce overtopping vulnerability.

As mentioned above, the USACE has already taken major steps to add concrete splash pads and/or to replace concrete I-walls with T-wall sections. This was laudable, and a very useful step with regard to addressing potential vulnerability associated with overtopping. It does not, however, also address the potential vulnerabilities associated with underseepage. At a recent press briefing a USACE representative at the IHNC east bank, at the west end of the Ninth Ward, indicated the massive concrete splash pads newly installed and remarked that "King Kong himself could not come over the top of that wall". Unfortunately, Katrina did not so much come over the top of that wall, as she passed beneath it.

Important lessons here include:

12. *It is important not to exonerate any failure mechanism(s) a priori, not before thorough analysis. This is true both in design, and in forensic investigations. In all cases, and especially in design, all failure mechanisms must be considered potentially guilty until either proven innocent, or until mitigated by appropriate design provisions.*

13. *Underseepage is one of the common modes of levee failure, and it appears to represent a considerable potential source of vulnerability throughout much of the New Orleans regional flood protection system. In addition to five sites studied in detail because failures (or incipient failures) due to underseepage occurred there, numerous additional sites were reviewed in a cursory manner and our investigation team was routinely struck by the surprisingly shallow depths of the sheetpile curtains, and the manner in which potential concerns regarding underseepage appeared to have been wished away during design. The installation of massively longer (deeper) sheetpiles, often 60 feet in length and more, replacing original sheetpiles less than thirty feet in length, as part of repairs at numerous breach sites represents a de facto and unusually frank admission as to the systemic inadequacy of pre-Katrina sheetpile penetrations. This is a potentially serious source of continuing risk to the regional system, and it may also obviate current cost projections for upgrading the regional system (and recent appropriations for this purpose as well.)*

14. *There is an urgent need to perform a thorough, system-wide review of potential underseepage-related vulnerability.*

In addition to the two major breaches at the east bank of the IHNC (at the west end of the Lower Ninth Ward), three additional breaches occurred on the west bank of the IHNC. These three breaches are Sites #5a, b and c. These were the first breaches to admit floodwaters into the main (downtown) protected basin. None of these three breaches managed to erode or scour a path back to the IHNC with a base consistently below sea level, however. Accordingly, although these breaches admitted floodwaters briefly while the water level within the IHNC was elevated, all three breaches subsequently ceased inflow as the storm subsequently subsided only a few hours later.

Site #5a was the west bank of the CSX railroad crossing. The failure at this site is particularly galling, as this site also failed during hurricane Betsy in 1965, so the repeat failure represents a very disconcerting failure to learn.

The rail crossing is part of a complex "penetration" through the federal IHNC frontage levees, as an adjacent roadway serving outboard side Port facilities crosses over the top of the federal frontage levee adjacent to the railroad line. Our investigation team was unable to learn just exactly who was overall in charge at this complex site with multiple overlapping jurisdictions; and that is a problem.

The rail line passes through a concrete T-wall structure with a rolling steel floodgate, so that the floodgate can be closed during storms to complete the perimeter frontage protection. Unfortunately, the steel gate had been damaged by a railroad accident several months prior, and it had been taken away for repairs. Accordingly, a temporary "sandbag levee" was erected across the missing floodgate opening; this washed away at some stage during hurricane Katrina. It is not clear who was in authority here, but the decision to remove the steel floodgate and allow trains to continue to operate, rather than affixing the damaged gate in place until it could be replaced, placed the entire community of the main (downtown) New Orleans protected basin (a population of approximately 250,000+) at risk. In hindsight, this was a difficult decision to justify.

Fortunately, the missing gate was not a principal source of flooding for the main (downtown) protected area. The main breach at this location was actually the result of composite action of the railroad embankment and the adjacent roadway section. Water appears to have passed first through the pervious gravel ballast at the top of the railroad embankment (representing the local "low spot" with regard to stopping flow), and it then eroded and undermined the adjacent roadway, resulting in a full breach. The levee embankment underlying the roadway appeared to consist in part of highly erodeable sands and shell-sands, and the presence of such highly erodeable soils without cut-off or other provisions to prevent catastrophic erosion was very ill-advised.

Lessons here include:

15. *Someone needs to be overall in charge at "penetrations" and "transitions" where multiple groups and functions intersect, and where overlapping responsibilities result. Whoever is in charge needs both to be made responsible for the overall situation, and they need to be granted adequate authority as to successfully execute that responsibility.*

16. *The continued operation of trains cannot be allowed to be considered more important than the safety of major urban populations.*

(7, repeated.) Highly erodeable embankment (and foundation) materials represent an intrinsic hazard, and their use should be avoided in flood protection systems defending significant populations.

(8, repeated.) When the use of such materials cannot be avoided, then great care should be taken to protect the sections by means of internal cut-offs, filters, and slope face protection (armoring) on the front and back faces and on the crest as well. Even then, the use of erosion-resistant soils is to be preferred if at all possible.

The other two breaches along this frontage occurred at the south end of the main Port of New Orleans. Both breaches occurred in full height earthen levee embankment sections that were comprised entirely of lightweight shell-sand fill. This was shocking to our investigators, and the lessons here are simple. Again

(7, repeated.) Highly erodeable embankment (and foundation) materials represent an intrinsic hazard, and their use should be avoided in flood protection systems defending significant populations.

(8, repeated.) When the use of such materials cannot be avoided, then great care should be taken to protect the sections by means of internal cut-offs, filters, and slope face protection (armoring) on the front and back faces and on the crest as well. Even then, the use of erosion-resistant soils is to be preferred if at all possible.

An additional set of partially developed erosional features occurred at a number of locations on the east bank of the IHNC at the west edge of the New Orleans East protected area. These are grouped together as "Site #7" in Figure 11.4 (and Table 11.1.) Overtopping occurred along much of this frontage, but the erosional distress systematically occurred at "transitions" between adjacent, disparate system elements (e.g. at transitions between full height earthen embankments and adjacent gated concrete floodwall segments, etc.) Here, again, it was transitions rather than the main segments themselves that proved problematic.

Our field investigation team were initially puzzled that these multiple features all appeared to be partially developed erosional features, on their way to failure but failing to reach full failure. As our studies progressed, however, it became clear that the lands on the inboard side were already filling with floodwaters as these features were developing, and this reduced the gradients and the durations of flow. It is not possible to know whether any of these features might have developed into full breaches if the inboard side lands had been more successfully defended against flooding from breaches that occurred at other locations. Lessons here thus include

(10, repeated.) "Transitions" where adjacent project elements join together were routinely problematic throughout much of the regional flood protection system. Successful design and construction of two adjoining project sections counts for little if the connection between them is not also successfully consummated. Significantly more attention needs to be paid to these "transitions".

17. The multiple transitions along this frontage suffered erosional damage but did not fully fail (and breach. But they may not have been fully tested as floodwaters were likely already rising on the inboard side lands as a result of massive breaches at other locations. These transitions should therefore be thoroughly re-evaluated as part of ongoing flood protection system upgrades.

11.3.5 The Lake Pontchartrain Frontage, and the Drainage Canals

As the eye of the hurricane finally passed to the northeast of New Orleans, its counter-clockwise swirling winds drove a final storm surge south along the shoreline of Lake Pontchartrain, along the north edge of the city.

This final storm surge produced some degree of overtopping at several locations along the lake frontage levees of the New Orleans East protected area, and two failures occurred (Sites #8a and b.) Site #8a was another complex "penetration" where multiple rights of way passed, together, through the federal levee perimeter. These included an elevated State highway, yet another railroad line, and a ground-level roadway. These three elements interacted poorly together; flow through the pervious railroad embankment ballast undermined the connection between a concrete floodwall protecting a support for the elevated highway and the adjoining surface roadway, and flow across these features also eroded an adjacent section of the Federal perimeter earthen levee. Once again, it was not clear who, if anyone, was overall in charge at this complex site. Thus

(15, repeated.) Someone needs to be overall in charge at "penetrations" and "transitions" where multiple groups and functions intersect, and where overlapping responsibilities result. Whoever is in charge needs both to be made responsible for the overall situation, and they need to be granted adequate authority as to successfully execute that responsibility.

The second site was a long section of floodwall whose crest was surprisingly low. Overtopping occurred along this low section over approximately a mile of floodwall length, despite a lack of persistent, sustained overtopping at any adjacent sections along this lakefront frontage. Significant scour occurred at the rear base of this floodwall, and a minor breach occurred at one location where floodwall panels shifted a bit as a result.

Farther to the west, the storm surge along the Pontchartrain Lake frontage levees at the north end of the main (downtown) New Orleans protected area did not produce meaningful overtopping along the lake frontage. This storm surge did, however, raise the water levels in three drainage canals that emptied into the Lake…. and three <u>major</u> breaches occurred along these drainage canals. These three breaches all rapidly scoured to well below sea level, and as a result floodwaters continued to flow in through these breaches for three days (even after the storm surge had subsided) eventually equilibrating with the still slightly elevated waters of Lake Borgne on Thursday, September 1st. These floodwaters infilled much of the main (downtown) New Orleans protected basin, resulting in roughly half of the overall deaths during hurricane Katrina, and a similar fraction of the damages as well.

The three drainage canals should never have been exposed to storm surge rise. The USACE had fought for years to install storm gates at the north ends of the three canals, but had been defeated (outmaneuvered in Congress) by local interests as a result of dysfunctional interactions and distrust between the local Levee Board (who were nominally responsible for perimeter levee protection) and the local Water and Sewerage Board (who were responsible for pumping and "unwatering" of New Orleans.) Every drop of rainwater that falls into New Orleans has to be pumped out, as the city is largely below sea level. Rainfall, and constant levee underseepage, are the principal concerns for "unwatering" on the part of the Water and Sewerage Board in most years, while the Levee Board is concerned primarily with providing protection during infrequent river floods and hurricanes. Accordingly these two organizations have differing principal focuses.

That led to dysfunctional interaction between them, distrust, and eventually even animosity. The Water and Sewerage Board, concerned that storm gates would be "perimeter protection" under the control of the Levee Board (and thus might possibly not be opened promptly when rainfall required pumping out through the drainage canals) fought successfully to have Congress decline the USACE's request for construction of storm gates at the heads of the canals.

Unfortunately, the construction of the floodgates would have been the superior technical solution. Instead, the canals remained "open" to Lake storm surges, and the three canals thus represented daggers pointed at the heart of New Orleans.

The USACE then attempted to exempt the three drainage canals (the 17th Street canal, the Orleans canal, and the London Avenue canal) from federal responsibility. Local interests again outmaneuvered the Corps, and Congress specifically declared these to be a federal responsibility; they required the USACE to raise the levels (elevations) of protection along the sides of these three canals.

The USACE correctly pointed out that the "footprints" available for levees along the sides of these canals (especially the 17th Street and London Avenue canals) were insufficient, as homeowners' properties abutting the canals encroached on the existing levees; in some cases property lines extended up the levee slopes to the edges of the narrow crests. There was insufficient room available to safely widen these levees in order to add to their heights.

This too was over-ruled, and the USACE was directed to raise the levels (elevations) of protection along these canals, within the existing (inadequate) "footprints" available. The results were catastrophic. Lessons here include

18. *The USACE is the lead Federal agency with expertise regarding levees and flood control. The USACE needs to be resolutely vocal and persistent in declining to undertake actions that it considers to be unsafe. Congress needs to better heed due warning from the Corps. The interactions between Congress and the Corps need to involve improved give-and-take; the Corps needs to be allowed to better assert strongly held professional opinions.*

19. *Local interests, and special interests, cannot be permitted to "outmaneuver" legitimate technical concerns with regard to Public Safety. The local Levee Board, and the local Water and Sewerage Board, should have been required to resolve their personal differences in the greater interest of Public safety.*

20. *The USACE felt that the path they were directed to follow was unsafe. They could have simply refused to take that path. That might have required resignations on the part of the leadership; those would have been honorable resignations.*

Having been essentially ordered to raise the levees (and floodwalls) along the three drainage canals, the USACE recognized that this posed significant technical challenges. Accordingly, they next performed a very well-directed full-scale experiment in the nearby Atchafalia River basin (on soil conditions very closely mirroring the challenging geology of the drainage canals) in which a concrete floodwall (I-wall) was modeled using a plain sheetpile wall. This test section (the E-99 test section) was constructed on the berm of an Atchafalia levee, with the berm height closely modeling the existing levee heights along the three drainage canals. A sheetpile cofferdam was constructed, and filled with water (to model storm surge loads against the sheetpile/floodwall).

This important large-scale field experiment clearly showed that under storm surge rise, a "gap" was likely to form between the sheetpile curtain supporting concrete I-walls, and that this gap would fill with water; significantly increasing the lateral pressures applied by water pressures against the sheetpiles/floodwalls. This mechanism subsequently figured in all three of the catastrophic drainage canal failures that occurred during hurricane Katrina, and in a number of other failures at other sites during Katrina as well. The failure to include this potential failure mode in the subsequent analysis and design of large elements of the regional flood protection system proved disastrous.

Unfortunately, the important lessons from this expensive and well-directed full-scale field test were never subsequently incorporated into the design of the floodwalls used to raise the protection elevations along the three drainage canals. Thus

21. Our investigation uncovered a persistent failure to learn; to adapt to technical advances, and even to heed the results of the USACE's own research, on the part of the New Orleans District. Outdated analysis methods, and strongly held views (which proved to be in error) were key failings in the design and construction of the flood protection system at a number of locations.

Another particularly important location was the south end of the Orleans drainage canal (Site #9.) Although it was located between the 17th Street drainage canal and the London Avenue drainage canal (catastrophic breaches occurred on both of these canals), no breaches occurred on the Orleans canal. Instead, storm surge waters simply flowed freely into the heart of New Orleans through an unfinished "gap" in the floodwalls lining this canal. A section of concrete floodwall approximately 200 feet in length at the south end of this canal was "omitted"; rendering the miles of floodwalls lining the remainder of the canal somewhat superfluous.

The omission of the last several hundred feet was done to protect the ancient (1904) brick building housing the several giant Woods pumps that pumped waters from the neighborhood into the canal (and thus into Lake Pontchartrain.) This brick building forms a "T" at the south end of the canal, closing the canal. When the canal water levels rise more than about five of six feet (e.g.: during pumping) , water seeps actively through the walls of the old brick building, and it is clear that significantly further rises in water levels would threaten to buckle the wall. Thus, either: (1) the Levee Board (who were responsible for "protection") would have had to erect a barrier to protect the Water and Sewerage Board's pump house , or (2) the Water and Sewerage Board would have had to expend their own resources to erect this protection themselves; helping out the Levee Board in the process by closing the end of the canal. As a result of internecine battling between these two agencies, and their inability to resolve their differences in the interest of the greater common good (and Public safety), neither occurred. Instead a gap was left in the floodwall (to control maximum possible canal water elevations (at Elev. +9 feet) and a "spillway" section was constructed across this gap until the matter could be further resolved.

(19, repeated.) Local interests, and special interests, cannot be permitted to "outmaneuver" legitimate technical concerns with regard to Public Safety. The local Levee Board, and the local Water and Sewerage Board, should have been required to resolve their personal differences in the greater interest of Public safety.

Eventually, however, floodwall systems were designed and constructed to raise the crest elevations of the levees along these three canals. A number of engineering errors, poor judgements, and poor decisions occurred during this process, and these too contributed to the three catastrophic breaches that occurred (at Sites #10, 11a, and 12b.) In addition, two "incipient" failures nearly occurred, but which were "saved" by nearby failures that rapidly drew down the canal water levels. One of these "near failures", on the west side of the 17th Street canal (Site #12a) would have resulted in flooding of a considerable portion of heavily populated Jefferson parish, and would have significantly increased the overall damages (and likely loss of life as well) from hurricane Katrina.

The first mistake was the failure to secure adequate right-of-way to widen the levees, to provide adequate embankment mass and weight as to sustain the increased lateral water forces that would be imposed by taller floodwalls atop the levee crests. This also meant lack of access and control over some of the inboard side levee faces and the critical inboard toe regions; rendering both inspections and necessary maintenance difficult.

These would both have disastrous consequences. Failure to purchase adequate right-of way contributed significantly to inadequate lateral stability at the massive breaches at the 17th Street canal (Site #12b) and at the west bank near the north end of the London Avenue canal (Site #11a.) Lack of control, and lack of access for inspection of the critical inboard toe areas led to rampant growth of trees at the toes (a known hazard), and even to excavations for swimming pools near the inboard toes of the levees in this critical region. This uncontrolled growth of trees appears to have contributed to the large failure on the east bank of the London Avenue canal (Site #10.)

(2, repeated.) The failure to purchase adequate right-of-way in what had become (expensive) developed neighborhoods resulted in initial project savings, but these cost-savings were <u>multiple orders of magnitude less</u> than the subsequent damages that occurred when these levee sections failed. ***Short-term cost savings in construction need to be balanced against the consequent increases in risk (the consequent reduction in likely reliability) for the resulting built system.***

22. The inboard toe region is a critical area with regard to both inspections and maintenance. Uncontrolled vegetation growth and other obstructions to maintenance and inspections need to be precluded. Large trees can die and leave rotted root systems that provide dangerous paths for seepage, and during hurricanes strong winds (and ground wetting which reduces root anchorage) routinely lead to toppling of trees. Trees on the inboard levee faces and the inboard toe regions can thus fall, leaving sudden voids that can cause or exacerbate "blowouts' and/or erosion and piping failures. Conditions *on the inboard side slopes and toes of considerable lengths of the levees lining both the London Avenue and 17th Street canals represented clear potential hazards in these regards.*

23. *In addition, it is customary policy for the USACE to require serviceable crest roads at the tops of levees to provide access for inspection, maintenance and emergency repairs. Given the failure to acquire adequate right-of-way, and resulting narrow crest widths, this was waived.*

The failure at the 17th Street canal was a lateral translational failure of the levee embankment, with the principal shear surface constrained by a thin, weak, and highly sensitive layer of organic clayey silt. Only one to several inches in thickness, this layer resulted from a previous hurricane that passed through; churning up organic matter, mixing it with the local silts and clays, and depositing a layer heavily flocculated clayey silt due to the storm-induced temporary increase in salinity of the local waters. This layer, which was only one to several inches in thickness, was well-hidden by an overlying layer of sticks and twigs and leaves, representing storm-blown detritus from the causative hurricane. This overlying layer obstructed conventional geotechnical sampling of this thin, sensitive layer, and also clear detection of this layer by conventional CPT.

The presence of this critical stratum went undetected by the original design studies, and by the post-event IPET forensic studies as well. The failure to detect this layer in both studies, despite drilling numerous boreholes through it, and pushing multiple CPT through it as well, was largely a result of employing "common practice" in which the field drilling (and CPT) were performed by personnel without special experience or geological expertise. The IPET team certainly had expert geological engineers, with experience with these types of strata, who could have usefully advised this process, but they were sidelined with other tasks (including writing up "geology" sections for the report.) There was segmentation (or compartmentalization) of the work both in the original design studies and in the subsequent forensic studies. Field personnel performing the drilling were insufficiently directed by engineers who had performed the important initial post-event forensic inspections, expert geologic input was insufficient, and the eventual analysts were not properly appraised of the full pertinent details by the other sub-teams.

That contrasts sharply with the approach taken by our (ILIT) team at this site. Despite considerable prior experience with these types of deposits, a thorough study was made of local geological nuances prior to beginning drilling and sampling (and CPT). Expert senior team members were present at the field boring and sampling, and the CPT, including specifically top-level expertise in geological engineering. Careful initial (immediate post-event) field forensics had already led to the suspicion that the failure was a lateral translational failure, controlled by a weak (and likely highly sensitive) layer occurring at a depth of approximately 3 to 8 feet beneath the inboard toe, producing laterally exiting toe features (including exiting overthrusts) to unusually great distances beyond the levee toe. Having studied the local geology, a highly sensitive organic clayey silt or silty clay layer (which might be very thin, and likely screened by overlying wind blow organic detritus) was a leading potential suspect. Our first boring discovered the failure stratum, and we then proceeded to follow it across the site (including sampling it at locations within the failure zone, at the toe of the displaced intact levee block, where the layer was clearly uni-directionally sheared and remoulded; incontrovertibly the failure surface.)

The lessons here include:

24. Engineering geology is of vital importance. Always has been, and always will be. It must be interwoven throughout all phases of geotechnical works; from pre-study, through site investigation, and through analysis and design as well. Geologists are too often treated as second class citizens, and some geotechnical firms no longer even "need" them. Failure to avail ourselves of expert geological insight, and at all stages of a project, is to needlessly imperil the effort.

25. Increasingly, the trend in "modern" practice is to segment geotechnical works; separating field investigation (e.g. borings and sampling, CPT, etc.), laboratory testing, analysis, and design. These elements need to be seamlessly interwoven, and iterative cross-communication between the personnel performing these needs to be thorough. Sadly, that is increasingly not the case; not only in government works, but in common (private) civil practice as well. This segmentation can be more "cost effective"…. The risk is that something will be missed.

In addition, review of the original design studies showed ten additional engineering lapses and/or questionable judgements at this site, as enumerated in Chapter 8; Section 8.3.7.1(c). These included extrapolation of data across excessive distances, failure to recognize "red flags" such as failure to recover samples at the same elevation in nearby borings (the elevation where the critical, sensitive, and very-difficult-to-sample organic clayey silt stratum occurred), etc. Readers are directed to this section for a full listing. Several key lessons include the following:

- Basic principles of soil mechanics were neglected, as the influence of increased effective stress beneath the centerline of the levee embankment was ignored, and soil shear strengths beneath the levee toes (where effective overburden stresses were smaller) were overestimated as a result. Shear strengths were extrapolated over lateral distances that were too great, and sometimes over excessive vertical distances. Shear strength profiles used for design calculations were not well-justified at certain, critical, elevation ranges by the data available.

- An archaic analysis method, the Method of Planes, was used for most stability calculations. This method (involving three blocks or wedges, and a conservative side force assumption between wedges) provides a demonstrated conservative answer for cases to which it can be applied. It is inflexible with regard to geometry, however, and was unable to deal with non-level stratigraphy and curvilinear failure surfaces. More modern and flexible methods were in common use at the time of these design studies, and should have been employed.

- The formation of a water-filled "gap" between the sheetpile curtain and the outboard portion of the levee embankment was not considered among the potential failure modes; despite the well-directed E-99 test section full-scale experiment that had shown this mode to be of concern.

- The design Factor of Safety for overall lateral stability during "transient" storm surges was only 1.30. That was far too low to allow an adequate margin for errors and uncertainties. That design Factor of Safety had evolved from tradition, and dated back to the middle of the last century, at which time it was selected for design of levees providing protection for agricultural lands (not populous regions). The design standard had not been updated, nor adapted for levees protecting large populations.

26. *All of these problems would have been expected to be caught and challenged by a competent panel of independent technical reviewers. Instead, reviews of the largely locally "outsourced" engineering design were performed internally within the USACE.* ***The mobilization of suitable, independent expert review capability is one of the most important steps that can be taken to enhance the likelihood of improved system reliability and performance in future events.***

27. *There was a persistent failure to learn, and to adapt to technical advances, within the local New Orleans District that affected performance of the regional flood protection system at numerous sites. Difficulties in recognizing potentially important "new" issues has continued in some cases since the hurricane; "That's not how we do it" needs to cease to be an issue…. On the heels of system-wide failure, changes are in order. The USACE needs to ensure that the New Orleans District is adequately technically staffed for the magnitude and technical difficulty of the challenges it faces with regard to the engineering design and construction of critical flood protections systems in a region with exceptionally challenging geology, and in the face of both local and federal governmental assistance/interference as well. Suitable technical advances need to be studied, and embraced if appropriate. Upgrading personnel, and education and training, will also be important.*

28. ***Design standards, especially with regard to targeted levels of system reliability, need to be reconsidered (see Figures 11.1 and 11.2).*** *This is already underway; the USACE is performing a comprehensive re-assessment of design procedures and standards, and treatment of flood protection systems on a risk-based systems basis is anticipated to be an important element of this. That is a very promising development.*

Two additional large failures (and breaches) occurred on the London Avenue drainage canal. The failure on the east bank, near the south end (Site #10) was the result of underseepage-induced erosion and piping and/or underseepage-induced hydraulic uplift at the inboard toe ("blowout"), and it may have been exacerbated by a large tree at the inboard toe of the levee that blew over during the storm (at approximately the location of the failure.) The failure on the west bank, near the north end, was an underseepage-induced lateral embankment stability failure; the embankment slid laterally, pushed by the increased canal water pressures, and shearing occurred along foundation soils whose strengths had been reduced by underseepage-induced pore pressure increases (and resultant reductions in effective stress.)

The principal lessons to be learned from these two additional cases are repeats of lessons cited previously, and will not be repeated here again.

11.4 References

Christian, John T. (2004), "Geotechnical Engineering Reliability: How well do we know what we are doing?" *J. of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 10, October 1, 2004.

IPET, (2006), "Performance Evaluation of the New Orleans and Southwest Louisiana Hurricane Protection System, Draft Final Report of the Interagency Performance Evaluation Task Force, Volume VI – The Performance – Interior Drainage and Pumping," available online: https://ipet.wes.army.mil/, date accessed: June 1, 2006.

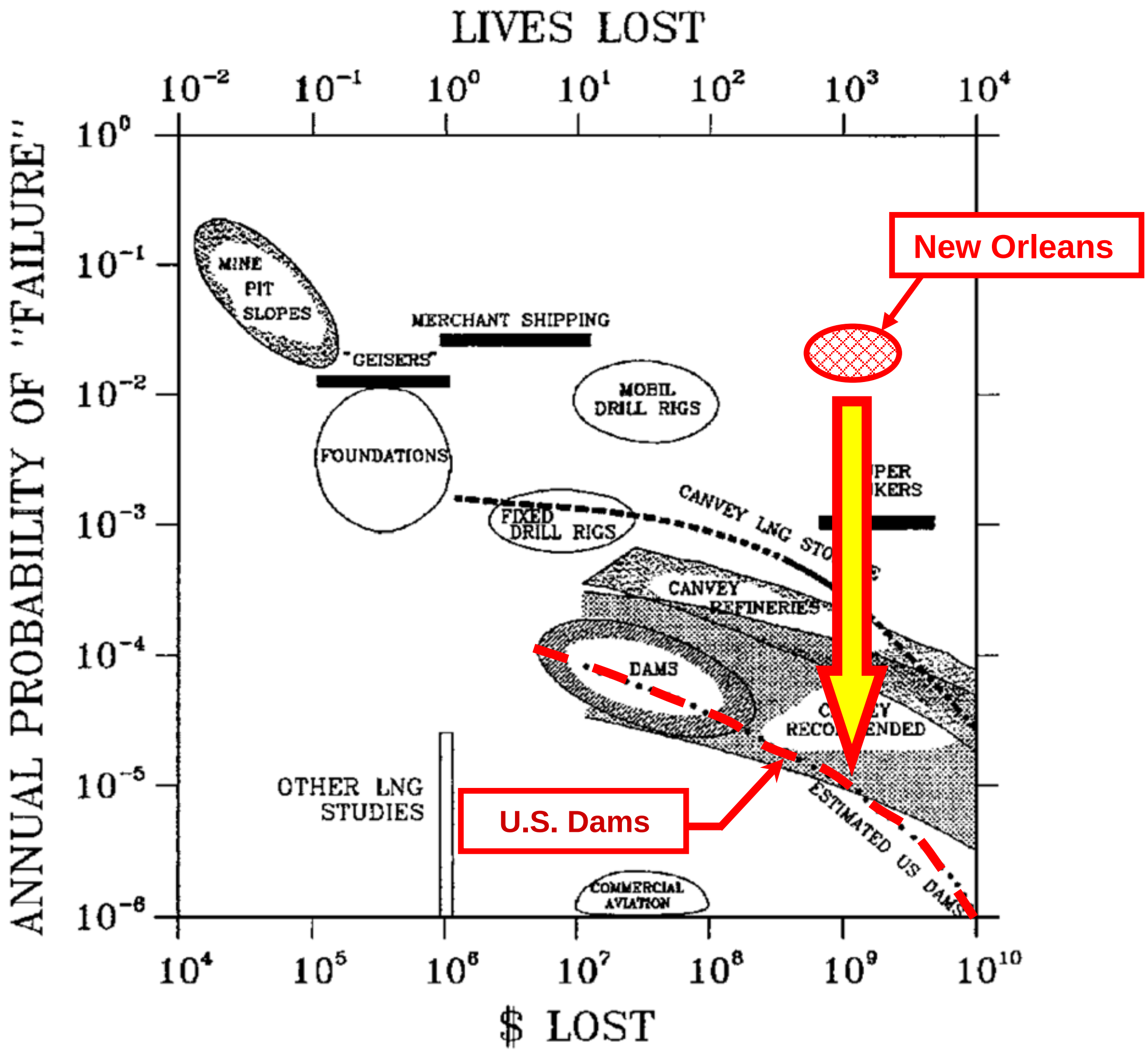

Figure 11.1: Risk plot showing the estimated pre-Katrina risk associated with the New Orleans regional flood protection system, and customary risk levels for current U.S. Practice with dams.

[Baseline Figure from Christian, 2004]

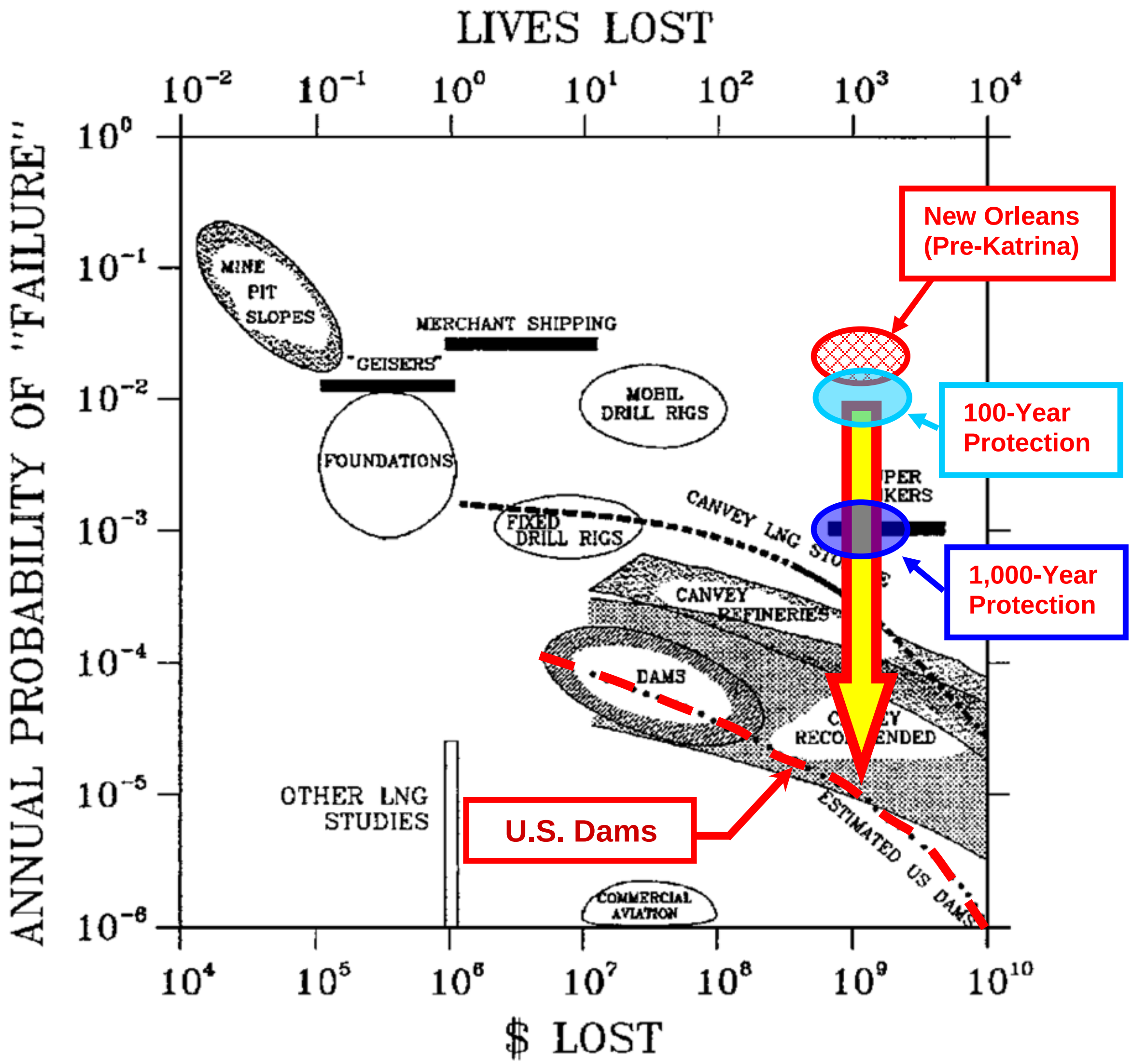

Figure 11.2: Risk plot showing the estimated pre-Katrina risk associated with the New Orleans regional flood protection system, and customary risk levels for current U.S. Practice with dams. Also shown are projected New Orleans risk levels for "successful" 100-year and 1,000-year storm and flood design.

[Baseline Figure from Christian, 2004]

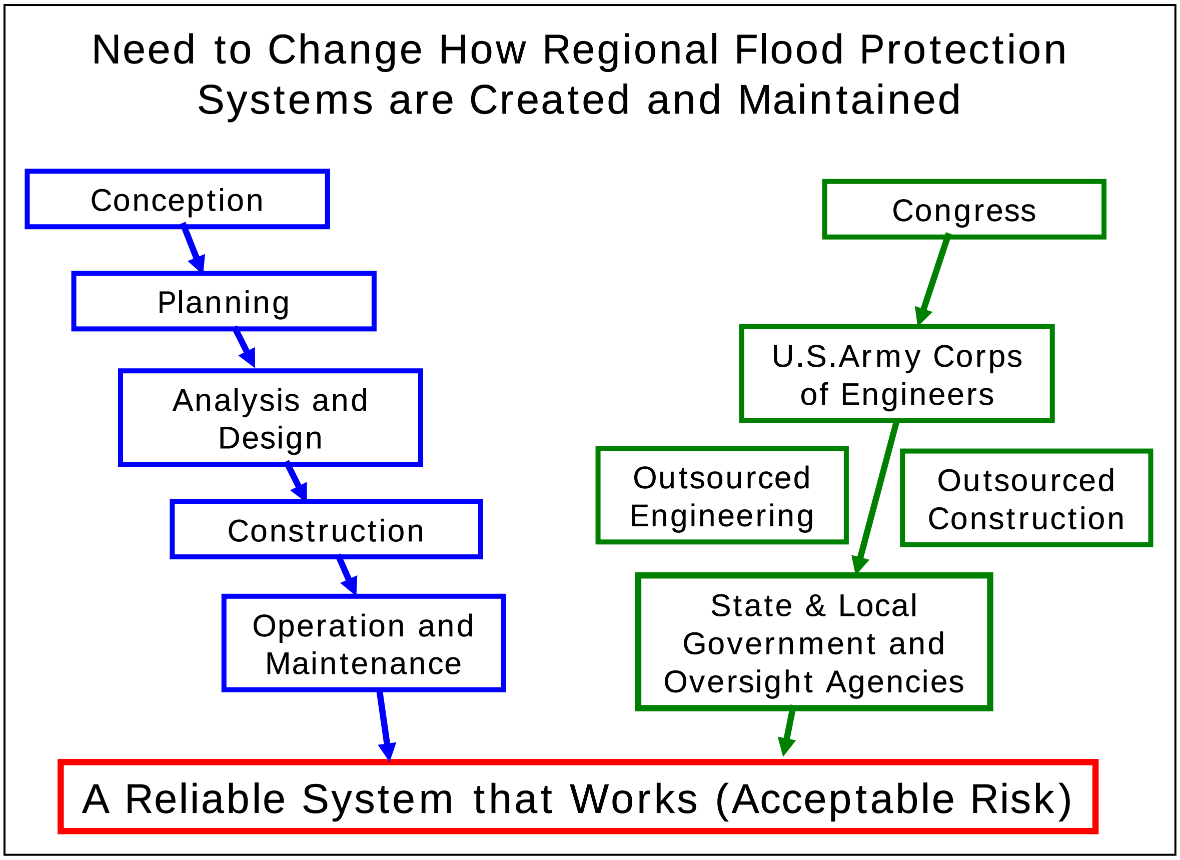

Figure 11.3: Engineering and organizational elements intrinsic to the creation, operation and maintenance of major U.S. regional flood protection systems in the Mississippi river basin.

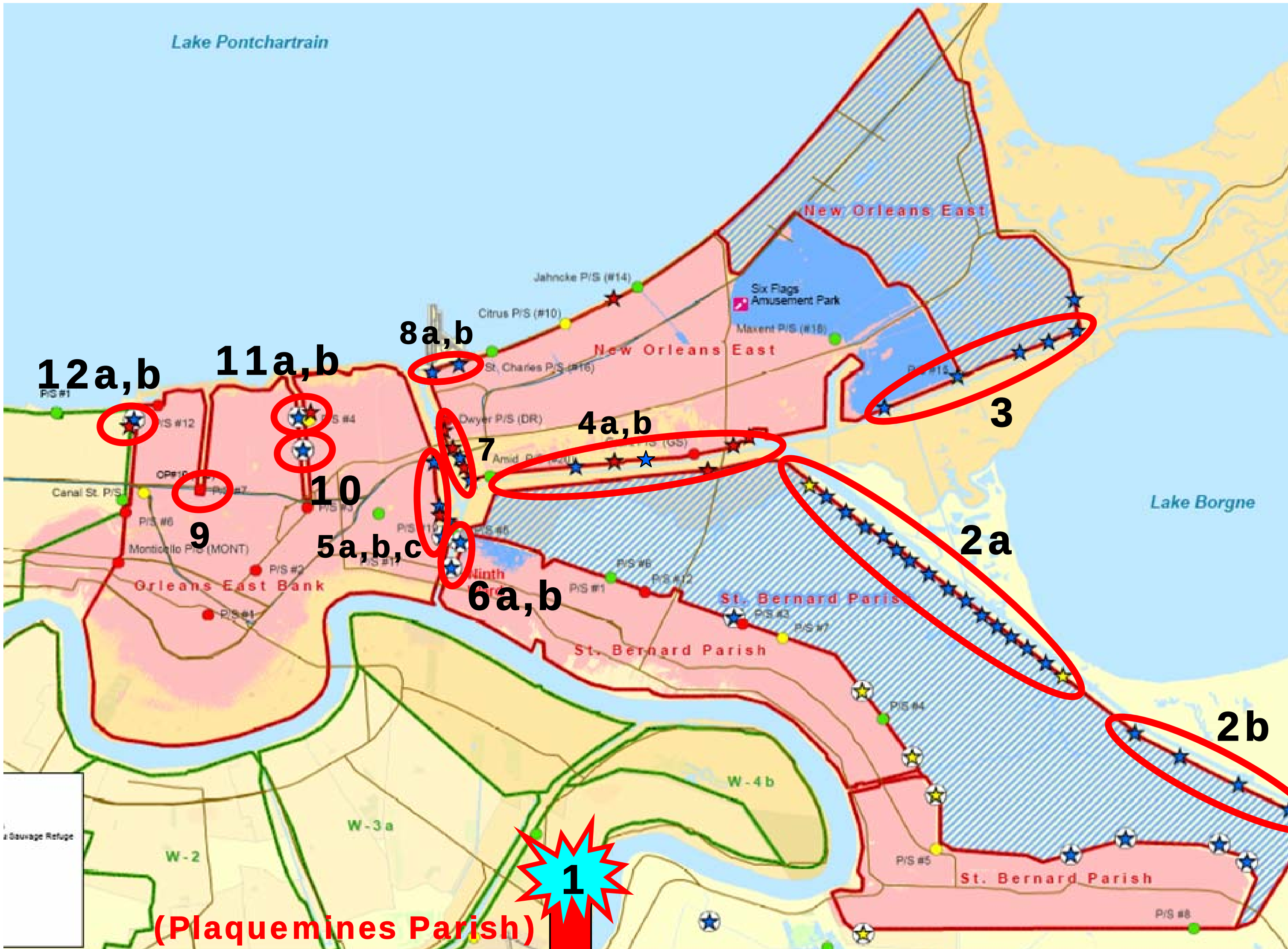

Figure 11.4: Summary of principal failures, breaches, and other locations of interest. (Blue stars mark breaches, red stars mark locations of distress.) [Base map provided by the USACE]

Table 11.1: Summary of Principal Damage Features Studied

Site No. or Group No.	General Location	Failure Mechanism and Cause (This Study: ILIT)	Failure Mechanism and Cause (IPET; June 1, 2006)	Severity of Consequences	Comments
1	Plaquemines Parish	Multiple failures resulting principally from massive and sustained overtopping.	Same as ILIT	Catastrophic	Storm surge and waves generally exceeded design levels.
2a	MRGO Frontage, St. Bernard Parish	Massive erosion and scour along many miles of levees due to waves, overtopping, through-flow, and use of highly erodeable embankment materials.	Overtopping erosion	Catastrophic	
2b	South MRGO Frontage, St. Bernard Parish	Erosion and scour along isolated sections of levees due to waves, overtopping, through-flow, and use of highly erodeable embankment materials.	Overtopping erosion	Catastrophic	
3	GIWW Frontage, southeast corner of New Orleans East	Massive erosion and scour along many miles of levees due to waves, overtopping, through-flow, and use of highly erodeable embankment materials.	Overtopping erosion	Catastrophic	
4a	North Bank of GIWW; the Citrus back levee floodwall	Overtopping of concrete I-wall, resulting in scour behind the wall, which was pushed sideways by elevated water levels.	Same as ILIT	Moderate	Consequences would have been more severe if other sections of the protected basin had not failed.
4b	North Bank of GIWW; sheetpile "transition" wall	Overtopping of concrete I-wall and sheetpile transitions resulting in scour behind the wall, which was pushed sideways by elevated water levels.	Same as ILIT	Moderate	Consequences would have been more severe if other sections of the protected basin had not failed.
5a	CSX Rail Crossing, west bank of IHNC	Poor coordination and poor interaction of multiple elements at a complex "penetration." Also, use of highly erodeable fill materials.	Rail gate absent	Moderate	
5b	Earthen levee embankment near south end of Port	Use of highly erodeable fill materials.	Overtopping erosion	Moderate	
5c	Second earthen levee embankment near the south end of the Port	Use of highly erodeable fill materials.	Overtopping erosion	Moderate	

Table 11.1 (cont'd)

Site No. or Group No.	General Location	Failure Mechanism and Cause (This Study: ILIT)	Failure Mechanism and Cause (IPET; June 1, 2006)	Severity of Consequences	Comments
6a	East bank of IHNC at edge of the lower Ninth Ward: South Breach	Underseepage-induced lateral transitional failure.	Overtopping of I-wall and scour	Catastrophic	
6b	East bank of IHNC at edge of the lower Ninth Ward: North Breach	Underseepage-induced erosion and piping and/or underseepage-induced hydraulic uplift at inboard toe.	Deep, semi-rotational foundation failure through soft clays	Catastrophic	
7	Cluster of minor erosion features at "transitions," east bank of IHNC	Erosion at inadequately detailed "transitions" between adjoining, disparate flood protection system segments.	- - -	Minor	Consequences might have been more serious if other sections of the protected basin had not failed.
8a	Erosional breach at northwest corner of New Orleans East	Erosional failure of another complex "penetration" where multiple interacted poorly as they crossed the perimeter levee system.	- - -	Moderate	Consequences might have been more serious if other sections of the protected basin had not failed.
8b	Overtopping and breach at floodwall behind Old Lakefront Airport	Overtopping of a surprisingly low floodwall, resulting in erosion behind the floodwall.	Same as ILIT	Moderate	
9	"Missing" floodwall section at south end of the Orleans Canal	Floodwall section omitted due to poor interactions between local oversight agencies.	- - -	Minor	
10	South breach on the east bank of the London Avenue drainage canal	Underseepage-induced erosion and piping and/or hydraulic "blowout" at the inboard toe.	Same as ILIT	Catastrophic	

Table 11.1 (cont'd)

Site No. or Group No.	General Location	Failure Mechanism and Cause (This Study: ILIT)	Failure Mechanism and Cause (IPET; June 1, 2006)	Severity of Consequences	Comments
11a	North breach on the west bank of the London Avenue drainage canal	Underseepage-induced lateral stability failure.	Same as ILIT	Catastrophic	
11b	Incipient failure on the east bank	Underseepage-induced lateral stability failure was beginning, when the west bank failure occurred and drew down the canal water level.	- - -	Negligible	This was nearly a fourth catastrophic failure along the drainage canals.
12a	Breach on the east bank of the 17th Street Canal	Lateral translational levee foundation failure on a highly sensitive layer of organic clayey silt embedded within "marsh" deposits.	Deeper, semi-rotational foundation failure within soft clays	Catastrophic	
12b	Incipient failure on the west bank	Deeper, semi-rotational foundation failure within soft clays.	- - -	Near miss	This would have flooded large portions of the adjoining and heavily populated Jefferson parish.